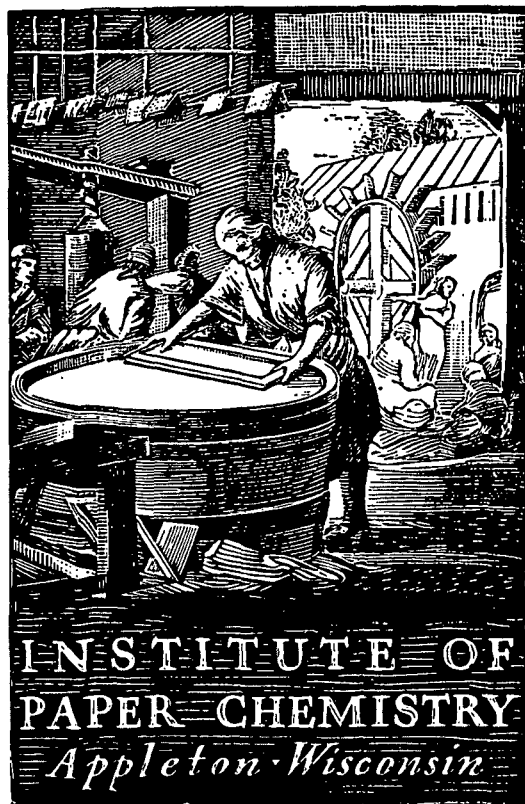


GENERAL



STUDY OF FACTORS INFLUENCING THE  
MECHANISM OF EDGEWISE COMPRESSION  
STRENGTH FAILURE

Project 2695-12

Report One  
A Summary Report  
to

FOURDRINIER KRAFT BOARD INSTITUTE, INC.

January 31, 1972

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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STUDY OF FACTORS INFLUENCING THE MECHANISM OF  
EDGEWISE COMPRESSION STRENGTH FAILURE

SUMMARY

The objective of this study was to investigate the way in which fiber bonding affects edgewise compression strength. This would provide information relative to the mechanisms involved in failure and possible ways of improving the compression strength of linerboard and corrugating medium. For this purpose a series of experiments were carried out with handsheets prepared in different ways so as to (a) vary the degree of bonding, and (b) the uniformity of bonding.

1. Considering the work as a whole, it appears that edgewise compression strength is dependent on at least two factors. They are (a) the compression-buckling strength of fiber segments, and (b) the number and strength of the fiber bonds. Thus, as the degree of bonding is increased from "low" levels, approximately proportionate increases in edgewise compression strength are obtained at first because more and stronger bonds are developed between fibers. The better bonding allows the fiber segments to support more load before they buckle and fail. However, beyond a certain level of fiber bonding, 10-12 kg./cm.<sup>2</sup> as measured by z-direction tensile strength in this study, edgewise compression strength is little affected by further increases in fiber bonding. Relatively large increases in z-direction tensile strength effect either no or slight increases in edgewise compression strength in this region. This suggests that fiber strength becomes the limiting factor above a certain degree of bonding.

2. The general effects of the specific ways of varying the degree and uniformity of bonding employed in this study were as follows:

- a. Small to large increases in z-direction tensile with much less than proportionate increases in edgewise compression strength.
  - (1) Formation variations due to increased consistency, flocculating agent (PEI), stock heating, and time in handsheet mold
  - (2) Wet strength bonding agent
- b. Small to large decreases in z-direction tensile strength with roughly proportional decreases in edgewise compression strength.
  - (1) Wetting agent
  - (2) Synthetic fiber addition

3. These results suggest that further work may be warranted in such areas as the following:

- a. The influence of fiber strength should be clarified. One approach would be to form sheets from synthetic fibers having different strength characteristics but varying the degree of bonding.
- b. Investigate various ways of processing papermaking fibers so as to retain more of their compressive potential — e.g., refine less so as to retain fiber strength and obtain bonding by beater additives.
- c. Past studies have shown that edgewise compression strength and tension stiffness ( $E_t$ ) are fairly well related. The present study suggests that such relationships might be strengthened if z-direction bonding and

other factors were also taken into account. In this connection, further consideration of the directional differences between Et and edgewise compression strength may be important.

## INTRODUCTION

It is well recognized that edgewise compression strength is one of the most important mechanical properties to be desired in linerboard and corrugating medium used for the production of corrugated boxes. It has been shown, for example, that top-load box compression is primarily a function of the cross-direction edgewise compression strength of the corrugated combined board. The edgewise compression of the combined board in turn is approximately equal to the sum of the edgewise compression strengths of the single-face liner, double-face liner, and the medium corrected for draw.

Studies carried out relative to the effect of process variables on edgewise compression have shown that edgewise compression strength of linerboard and corrugating medium is essentially linearly related to basis weight, freeness, extensional stiffness, and z-direction tensile. As would be expected, basis weight is best correlated to edgewise compression and z-direction tensile, which is a measure of the fiber bonding, exhibits the poorest correlation of those mentioned above.

At the time the present study was initiated it was felt that failure of the edgewise compression test specimen was triggered by a localized delamination resulting from bond failure of the fiber. This would decrease the ability of the specimen to resist the externally applied compression stress and the specimen would fail by localized buckling. Thus, compression strength of a structure such as paperboard was believed to be markedly dependent on the weakest link or unit in the structure. The weak or poor correlation of edgewise compression and z-direction tensile mitigate against the foregoing hypothesis. Because of this and other factors such as the fact that, with the exception of basis weight,

edgewise compression is only weakly influenced by many process variables, a study was undertaken to investigate the mechanism of initial failure in the edgewise compression specimen. It was hoped to be able to determine the type of stress and, hence, how the properties of the fiber and the degree of bonding in linerboard and corrugating medium govern edgewise compression. Therefore, a series of different but coordinated experiments were carried out with handsheets involving different ways of (a) varying the degree of bonding, and (b) the uniformity of bonding within the test specimen. The varying degrees of fiber-fiber bonding were monitored directly by means of z-direction tensile strength and the effect on edgewise compression was followed by the modified ring compression test.



## MATERIALS AND TEST PROCEDURES

In order to ascertain the correctness of the hypothesis that the higher the fiber bonding the higher the edgewise compression the following series of experiments were carried out in which test handsheets were made under varying conditions affecting fiber bonding:

### 1. Varying bonding by boiling

It is well known that if a beaten stock is heated the higher the temperature level or the longer the boiling period, the higher will be the freeness. The heating presumably decreases the degree of swelling and, hence, the freeness increases. By this technique it is possible to change the freeness and, hence, bonding potentials without change in fiber length. Two sets of partially unbonded sheets were also made using Triton X-100.

In this series of experiments unbleached kraft pulp was refined to 350-ml. freeness C.S. and made into 2.5-g. handsheets (26 lb./M ft.<sup>2</sup>) in a British sheet mold.

- a. Control, 2.5-g. handsheet at 350-ml. freeness.
- b. Same as a above, except stock brought to boil, then immediately cooled to room temperature and made into 2.5-g. handsheets.
- c. Same as b above, except stock boiled for 5 minutes, cooled and made into 2.5-g. handsheets.
- d. Same as b above, except stock boiled for 15 minutes, cooled and made into 2.5-g. handsheets.

e. Unbonded sheets

- (1) Same as a above, except that 1% (based on volume of water in mold) Triton X-100 was added to the stock in the mold, mixed and then made into 2.5-g. handsheets.
- (2) Same as a above, except that 3% (based on volume of water in mold) Triton X-100 was added to the stock in the mold, mixed and then made into 2.5-g. handsheets.

2. Varying bonding by modifications in formation

The purpose of the experiments in this phase was to vary bonding by modification of the sheet formation via flocculation.

- a. Control, 2.5-g. unbleached kraft pulp, refined to 350-ml. freeness C.S., was diluted with 7000 ml. of water and made into handsheets in a British handsheet mold.
- b. Same as 2-a above, except dilution water was reduced to 5250 ml.
- c. Same as 2-a above, except dilution water was reduced to 3500 ml.
- d. Same as 2-a above, except dilution water was reduced to 1750 ml.
- e. Same as 2-a above, except that stock was held for 1.5 seconds after stirring before mold drain was opened.
- f. Same as 2-a above, except that stock was held for 3.0 seconds after stirring before mold drain was opened.
- g. Same as 2-a above, except that stock was held for 30.0 seconds after stirring before mold drain was opened.
- h. Same as 2-a above, except that either 0.5 or 1% (based on fiber content) Cytame 5 was added as a deflocculant.
- i. Same as 2-a above, except that 0.5% (based on fiber content) polyethylenimine (Dow Chemical Co.) was added as a flocculating agent.

- j. Same as 2-i above, except 1% polyethyleimine was added as a flocculating agent.

### 3. Effect of localized flaws

Localized flaws were introduced in the sheet in an attempt to determine if the presence of a flaw could be related to edgewise compression strength and also the onset of failure in the edgewise compression test. The localized flaws were introduced in two different ways as set forth below:

#### a. Unbonded fiber

- (1) Control, 2.5-g. handsheets were made from unbleached kraft pulp which had been refined to 350 ml.
- (2) Same as 3-a-(1) above, except unbonded rayon fibers were added (No. 8001-00 Rayon 3.0dpf, 5/16-inch cut, no finish) to give 99:1 unbleached kraft:rayon.
- (3) Same as 3-a-(2) above, except ratio of unbleached kraft to rayon fiber was 95:5.
- (4) Same as 3-a-(2) above, except ratio of unbleached kraft to rayon fiber was 90:10.
- (5) Same as 3-a-(2) above, except ratio of unbleached kraft to rayon fiber was 80:20.
- (6) Same as 3-a-(2) above, except ratio of unbleached kraft to rayon fiber was 70:30.

#### b. Dry tissue insert

It had been planned to incorporate a multiplicity of unbonded rayon fibers in strategic locations in the kraft sheet; however, it

was subsequently found that narrow strips of 13-lb. dry toilet tissue worked more effectively than the rayon fibers. Accordingly, thin strips of dry toilet tissue were centrally placed between two handsheets which were subsequently wet laminated. The experimental sheets made were as follows:

- (1) Control. Two 1.25-g. handsheets (13-lb./M ft.<sup>2</sup>) handsheets of unbleached kraft pulp refined to 350 ml. were wet laminated to form a 2.5-g. handsheet.
- (2) Same as 3-b-(1) above, except that a 1/16 x 1-inch strip of dry toilet tissue was placed in a central position between the sheets before wet laminating so that test specimens for edge-wise compression and z-direction tensile could be cut with the tissue centered on the specimen.
- (3) Same as 3-b-(2) above, except used 1/8 x 1-inch strip of toilet tissue.
- (4) Same as 3-b-(2) above, except used 1/4 x 1-inch strip of toilet tissue.
- (5) Control. Consisted of one 17-lb. and one 13-lb./M ft.<sup>2</sup>, unbleached kraft pulp refined to 350 ml., wet laminated.
- (6) Same as 3-b-(5) above, except placed 1/16 x 1-inch strip of dry toilet tissue between sheets before wet laminating so as to be centrally located.
- (7) Same as 3-b-(6) above, except strip of dry toilet tissue was 1/8 x 1 inch.
- (8) Same as 3-b-(6) above, except strip of dry toilet tissue was 1/4 x 1 inch.

4. Effect of varying degrees of debonding on edgewise compression at three levels of initial freeness

In this phase unbleached kraft pulp was refined to three levels of freeness, namely, 450, 350, and 250-ml. C.S. At each level of freeness 2.5-g. test handsheets were prepared at nine different levels of debonding agent. The experimental conditions used at each freeness level were:

- a. Control, 2.5-g. handsheets.
- b. Same as 4-a above, except added 0.005% Triton X-100 (based on volume of water in mold).
- c. Same as 4-b above, except added 0.010% Triton X-100.
- d. Same as 4-b above, except added 0.025% Triton X-100.
- e. Same as 4-b above, except added 0.050% Triton X-100.
- f. Same as 4-b above, except added 0.100% Triton X-100.
- g. Same as 4-b above, except added 0.200% Triton X-100.
- h. Same as 4-b above, except added 0.400% Triton X-100.
- i. Same as 4-b above, except added 0.800% Triton X-100.

5. Use of wet strength resin

A series of handsheets containing different amounts of wet strength resin (Parez 607) was made to provide handsheets exhibiting a wide range of z-direction tensile strengths. For this series of experiments unbleached kraft pulp was refined to 350-ml. freeness C.S. and used to prepare the following experimental handsheets:

- a. Control, 2.5-g. handsheet. No resin but pH of 5.5-6.0.
- b. Same as 5-a above, except added 0.2% wet strength resin (based on fiber) at a pH of 5.5-6.0.

- c. Same as 5-b above, except resin addition of 0.40%.
- d. Same as 5-b above, except resin addition of 0.80%.
- e. Same as 5-b above, except resin addition of 1.60%.
- f. Same as 5-b above, except resin addition of 3.20%.
- g. Same as 5-b above, except resin addition of 6.40%.

The airdry handsheets obtained in this series were cured for one hour in an oven whose temperature was controlled at 105°F.

## 6. Evaluation

Prior to evaluation all experimental handsheets were conditioned at  $50 \pm 2.0\%$  relative humidity at  $73 \pm 3.5^\circ\text{F}$ . prior to testing. For each experimental condition the handsheets were evaluated in terms of basis weight, caliper, edgewise compression, and z-direction tensile. The z-direction tests were carried out using the procedure described by Wink and Van Eperen (1).

## DISCUSSION OF RESULTS

As mentioned previously, it was hypothesized that failure occurs in an edgewise compression test specimen because fiber-to-fiber bond failure in a localized region causes local delamination and buckling in such regions. Consequently, it was expected that edgewise compression strength should be highly related to bonding in the thickness direction and the study was designed to investigate this relationship among other things. Accordingly, experiments were carried out in which handsheets were prepared under a variety of conditions which affect fiber bonding.

Certain results developed during the course of the work suggest that the above hypothesis does not fully explain the facts. Specifically, it was observed that increases in bonding strength (as measured by z-direction tensile) above a certain level caused only small changes in edgewise compression strength. In contrast, edgewise compression strength and bonding strength were fairly well related at "lower" bonding strength levels. The implications of this behavior are discussed in the concluding section of the report.

## FORMATION EFFECTS

In this phase of the study sheet formation was varied by (a) increasing the consistency in the mold, (b) holding the stock in the mold for varying lengths of time, and (c) employing flocculating and deflocculating agents. The results obtained are summarized in Table I.

In Experiments 2B-2D, the consistency in the mold was varied by using 25, 50, and 75% less water than normal. It would be expected that this would result in less uniform formation due to flocculation and, hence, a somewhat

TABLE I  
EFFECT OF VARIATIONS IN FORMATION ON BONDING AND MODIFIED RING COMPRESSION

Experiment	Conditions	Freeness, cc.	Basis Weight, 2 lb./M ft.	Caliper, pt.	z-Direction Tensile, <sup>2</sup> kg./cm.	Diff., % <sup>a</sup>	Mod. Ring Compression, lb./in.		Diff., % <sup>a</sup>
							As Tested	Adjusted <sup>b</sup>	
2A	Control	350	28.6	7.3	11.3	--	18.5	16.8	--
2B	25% less water in mold		28.8	7.2	13.9	+23.0	18.9	17.1	+ 1.8
2C	50% less water in mold		27.6	7.1	12.7	+12.4	17.2	16.2	- 3.6
2D	75% less water in mold		28.3	7.6	13.1	+15.9	18.5	17.0	+ 1.2
2E	Stock held 1.5 sec. in mold		28.9	7.2	12.2	+ 8.0	19.4	17.5	+ 4.2
2F	Stock held 3.0 sec. in mold		28.2	7.2	13.0	+15.5	18.6	17.1	+ 1.8
2G	Stock held 30.0 sec. in mold		28.1	7.2	12.6	+11.5	18.5	17.1	+ 1.8
2H-1	1.0% defloc. agent (Cytame 5)		28.8	7.2	12.7	+12.6	19.2	17.3	+ 3.0
2H-2	0.5% defloc. agent (Cytame 5)		29.2	7.2	12.5	+15.4	19.9	17.7	+ 5.4
2I-1	0.5% floc. agent (PEI)		28.6	7.3	18.1	+60.2	19.1	17.4	+ 3.6
2I-2	1.0% floc. agent (PEI)		28.2	7.2	17.5	+54.9	19.5	18.0	+ 7.1
2J	Control	350	28.0	7.2	11.4	--	18.0	16.7	--
2K	Stock held in mold 1.0 min.		28.1	7.5	12.5	+11.1	19.0	17.6	+ 5.4
2L	Stock held in mold 5.0 min.		28.4	7.2	12.0	+ 5.3	20.5	18.8	+12.6
2M	Stock held in mold 10.0 min.		28.0	7.1	11.9	+ 4.4	19.8	18.4	+10.2
2N	Stock held 0.5 min. + 0.5% PEI		28.2	7.8	14.4	+28.8	19.2	17.7	+ 6.0
2O	Stock held 1.0 min. + 0.5% PEI		28.5	8.0	14.9	+30.7	20.8	19.0	+13.8
2P	Stock held 3.0 min. + 0.5% PEI		28.2	7.9	15.3	+34.2	19.8	18.3	+ 9.6
2Q	Stock held 5.0 min. + 0.5% PEI		28.4	7.8	14.7	+28.9	19.8	18.1	+ 8.4

<sup>a</sup>Based on Control as reference.

<sup>b</sup>Adjusted to a basis weight of 26 lb./M ft.<sup>2</sup>



lesser degree of fiber alignment in the plane of the sheet. As may be noted, the z-direction tensile results increased from about 12 to 23% as would be expected. However, there was substantially no change in modified ring compression strength.

Similar results were obtained in the experiments wherein the stock was held in the mold for 1.5, 3, and 30 sec. (Experiments 2E-2G). In general, it was expected that the longer retention times in the mold would result in less uniform formation and increase z-direction tensile strength as well as modified ring compression strength. However, the edgewise compression results show little or no change relative to the control for the modest increases in z-direction tensile strength achieved in this series of experiments.

As another means of varying the formation of the sheet, the effects of flocculating and deflocculating agents were studied in Experiments 2H, 2I, and 2N through 2Q. The flocculating agent employed was polyethylenimine (PEI). It should be mentioned that PEI has been used in papermaking operations to attain such objectives as improved drainage, wet strength, improved mechanical properties, etc. While it serves as an effective flocculating agent it is not entirely clear whether the improved properties that often result from its use are entirely due to flocculation or are also due to increased bonding strength. With this in mind, Experiments 2I-1, -2 show that z-direction tensile strength increases of about 55-60% were achieved at the 0.5 and 1.0% PEI addition levels. Despite the large increases in z-direction tensile only small increases of 3.6 and 7.1% were obtained for modified ring compression. In the second set of experiments with PEI (No. 2N-2Q) the increases in z-direction tensile strength ranged from about 28 to 34% while ring compression only increased from 6 to 13.8%. Qualitatively, in the case of both experiments, fairly large increases

in z-direction strength are associated with much smaller changes in modified ring strength, although the absolute magnitudes of the percent changes do not appear to be entirely consistent in the 2H and 2N-2Q experiments. It may be noted that in Compression Report 84 an 80.9% increase in z-direction tensile strength was achieved with PEI but this resulted in only a 17.2% change in modified ring strength. This is qualitatively similar to the results obtained herein. Also in that work, it may be significant to note that PEI had little or no effect on tensile stiffness and modulus although tensile strength increased 11.7%. Perhaps increases in bonding which are not accompanied by significant increases in stiffness do not have a substantial effect on edgewise compression strength.

The use of Cytame 5 as a deflocculating agent resulted in small increases in z-direction tensile strength and modified ring strength. In Compression Report 84 when deacetylated Karaya gum was used as a deflocculating agent there was essentially no change in z-direction tensile and a slight decrease in ring strength.

#### RESIN BONDING AGENT

As another means of increasing the bonding strength and sheet without affecting the intrinsic strength of the fibers, sheets were prepared with varying amounts of a wet strength resin (Parez 607). Referring to Table II, or Fig. 1, it may be noted that the fiber-to-fiber bonding as measured by z-direction tensile strength increased rapidly with increases in resin content up to about 3%. On the other hand, the large increases in z-direction tensile strength did not produce an equivalent increase in modified ring strength. For example, at 3.2% resin content modified ring strength was only 14.9% higher than the control while

z-direction tensile strength was 96.1% higher than the control. It seems apparent from these and the previous results that increasing the fiber bonding beyond a certain level produces only small improvements in modified ring strength for the conditions of these experiments.

TABLE II

EFFECT OF RESIN BONDING AGENTS ON EDGEWISE COMPRESSION

Condition	pH	Basis Weight, lb./M ft. <sup>2</sup>	Caliper, pt.	Modified Ring Compression, lb./in.		Diff., % <sup>b</sup>	z-Direction Tensile, kg./cm. <sup>2</sup>	Diff., % <sup>b</sup>
				As Tested	Adj. <sup>a</sup>			
Control	5.9	27.1	7.1	18.9	18.1	--	10.4	--
0.2% Resin	5.9	27.5	7.1	18.6	17.7	- 2.2	11.4	+ 9.6
0.4% Resin	5.9	29.7	7.9	21.3	18.6	+ 2.8	11.0	+ 5.8
0.8% Resin	5.9	28.0	7.3	20.5	19.0	+ 5.0	13.1	+26.0
1.6% Resin	5.6	28.0	7.5	21.4	19.9	+ 9.9	16.6	+59.6
3.2% Resin	5.4	28.4	7.4	22.7	20.8	+14.9	20.4	+96.1
6.4% Resin	4.8	28.5	7.5	23.1	21.1	+16.6	20.2	+94.2

<sup>a</sup>Adjusted to 26 lb./M ft.<sup>2</sup> basis.

<sup>b</sup>Based on Control as reference.

Note: C.S. freeness of Control was 350 cc.

It is believed that the above results are in line with the general behavior obtained with various impregnants. It has been often found that low levels of impregnation produce little improvement in edgewise compression strength. It appears that significant improvements are most often obtained when the addition level is high enough to produce a secondary structure within the sheet which can resist load.

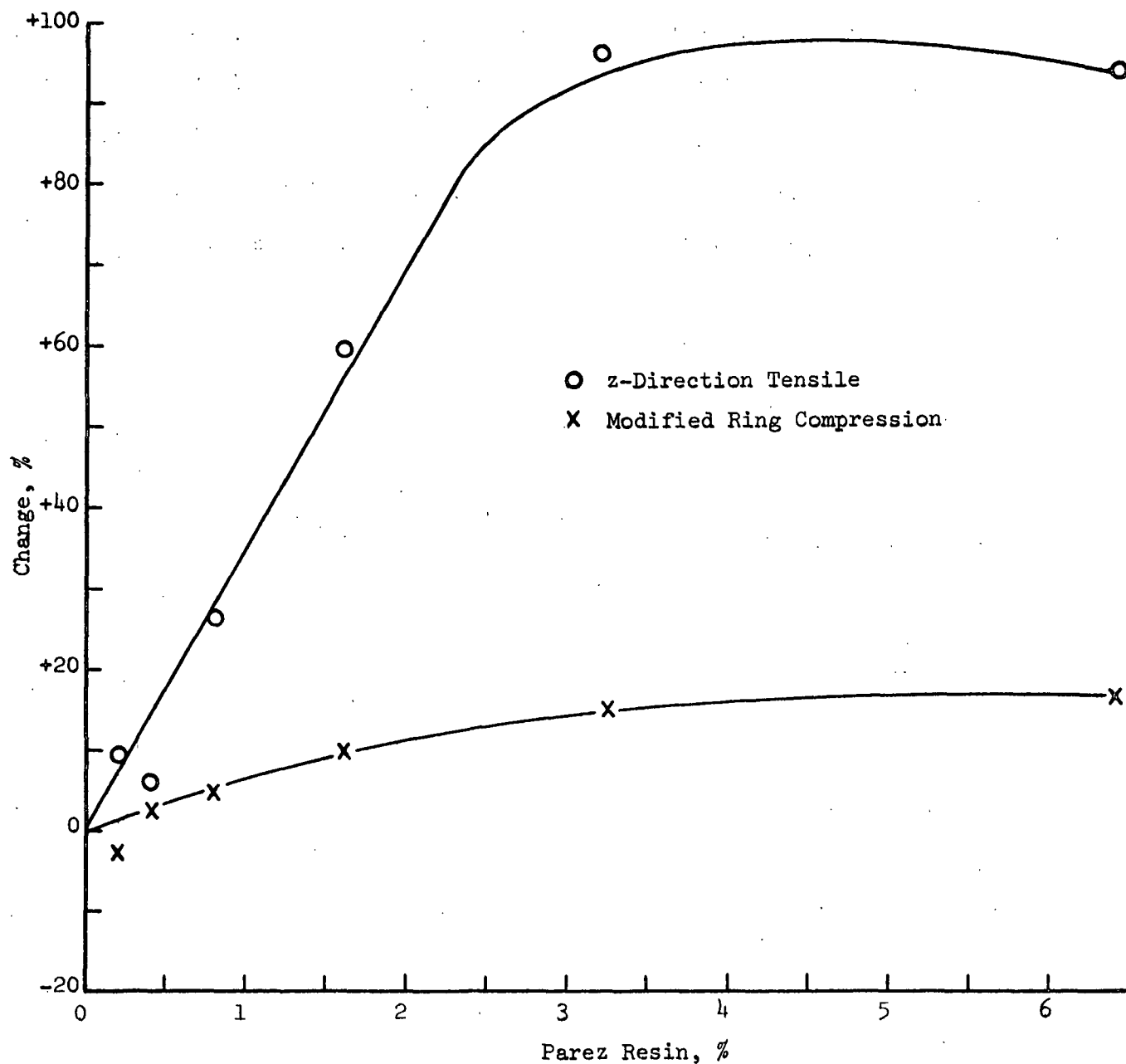


Figure 1. Effect of Resin Bonding Agent on z-Direction Tensile and Modified Ring Compression Strength

## WETTING AGENTS

In the previous phase a resin was used to increase the bonding. This presumably had little or no effect on fiber strength. In this phase reductions in bonding strength were effected by using a wetting agent — Triton X-100. The results obtained in an exploratory trial are shown in Table III. Large reductions in bonding strength were obtained using the wetting agent as would be expected. Also, large reductions in modified ring strength were also obtained.

TABLE III

### EFFECT OF A WETTING AGENT ON BONDING AND RING COMPRESSION

Exp. No.	Conditions	Basis Weight, lb./M ft. <sup>2</sup>	Caliper, pt.	z-Direction Tensile, kg./cm. <sup>2</sup>	Diff., % <sup>a</sup>	Modified Ring Compression, lb./in. <sup>b</sup>	Diff., % <sup>a</sup>
1A	Control	27.9	7.2	11.0	--	17.8	--
1E1	Control + 0.1% Triton X-100	30.0	8.0	3.9	-64.8	10.5	-41.0
1E2	Control + 1.0% Triton X-100	38.6	10.8	1.8	-83.4	3.8	-78.7

<sup>a</sup>Based on Control as reference.

<sup>b</sup>Corrected to 26 lb./M ft.<sup>2</sup>

To study the effect of reductions in bonding strength in greater detail handsheets were prepared using a wide range of concentrations of Triton X-100. Three freeness levels were employed, namely, 250, 350, and 450-cc. C.S. The results obtained are summarized in Table IV. Figure 2 illustrates the relationship between z-direction tensile strength and modified ring strength for the 350-cc. freeness sheets. Referring to the table or Fig. 2 it may be noted that

TABLE IV  
EFFECT OF VARYING BONDING BY MEANS OF A WETTING AGENT

Experiment	Conditions	Freeness, cc.	Basis Weight, lb./M ft.	Caliper, pt.	z-Direction Tensile, kg./cm. <sup>2</sup>	Diff., % <sup>a</sup>	Mod. Ring Compression, lb./in. As Tested	Mod. Ring Compression, lb./in. Adjusted <sup>b</sup>	Diff., % <sup>a</sup>
4-A	Control - 0% Triton X-100	450	28.5	8.0	9.4	--	19.5	17.8	--
4-B	Control + 0.005% Triton X-100		28.1	8.0	7.0	-25.5	16.0	14.8	-12.8
4-C	Control + 0.010% Triton X-100		28.8	8.2	6.9	-26.6	15.9	14.4	-19.1
4-D	Control + 0.025% Triton X-100		28.0	8.2	5.1	-45.7	12.7	11.8	-33.7
4-E	Control + 0.050% Triton X-100		28.2	8.4	5.3	-43.6	12.1	11.2	-37.1
4-F	Control + 0.100% Triton X-100		29.0	9.0	5.1	-45.7	12.5	11.2	-37.1
4-G	Control + 0.200% Triton X-100		28.3	8.4	5.0	-46.8	11.9	10.9	-38.9
4-H	Control + 0.400% Triton X-100		28.3	9.0	4.7	-50.0	10.8	9.9	-44.4
4-I	Control + 0.800% Triton X-100		28.3	8.7	4.7	-50.0	10.4	9.6	-40.4
4-J	Control - 0% Triton X-100	350	29.0	7.3	11.1	--	20.2	18.1	--
4-K	Control + 0.005% Triton X-100		30.0	8.0	9.2	-17.1	18.3	15.9	-12.2
4-L	Control + 0.010% Triton X-100		27.9	8.0	7.8	-29.7	14.1	13.1	-27.6
4-M	Control + 0.025% Triton X-100		28.7	8.0	5.6	-49.5	14.2	12.9	-28.7
4-N	Control + 0.050% Triton X-100		29.4	8.6	5.1	-54.2	13.3	11.8	-34.8
4-O	Control + 0.100% Triton X-100		30.3	8.5	5.5	-50.5	14.1	12.1	-33.1
4-P	Control + 0.200% Triton X-100		29.8	8.4	5.3	-52.3	12.5	10.9	-39.8
4-Q	Control + 0.400% Triton X-100		31.1	9.0	5.2	-53.2	12.8	10.7	-40.9
4-R	Control + 0.800% Triton X-100		29.5	8.1	6.1	-45.0	13.8	12.2	-32.6
4-S	Control - 0% Triton X-100	250	28.8	7.2	11.9	--	19.2	17.3	--
4-T	Control + 0.005% Triton X-100		28.9	7.8	9.9	-16.8	18.1	16.3	-5.8
4-U	Control + 0.010% Triton X-100		27.9	7.9	8.8	-26.1	16.4	15.3	-11.6
4-V	Control + 0.025% Triton X-100		28.9	8.0	7.8	-34.4	13.1	11.8	-31.8
4-W	Control + 0.050% Triton X-100		29.9	8.3	6.9	-42.0	13.7	11.9	-31.2
4-X	Control + 0.100% Triton X-100		30.6	8.3	6.3	-47.1	14.1	12.0	-30.6
4-Y	Control + 0.200% Triton X-100		29.0	8.1	6.0	-49.6	12.6	11.3	-34.7
4-Z	Control + 0.400% Triton X-100		29.7	8.1	6.0	-49.6	12.7	11.1	-35.8
4-AA	Control + 0.800% Triton X-100		29.1	8.0	6.2	-47.9	12.2	10.9	-37.0

<sup>a</sup>Based on Control as reference.

<sup>b</sup>Adjusted to 26-lb. basis weight.

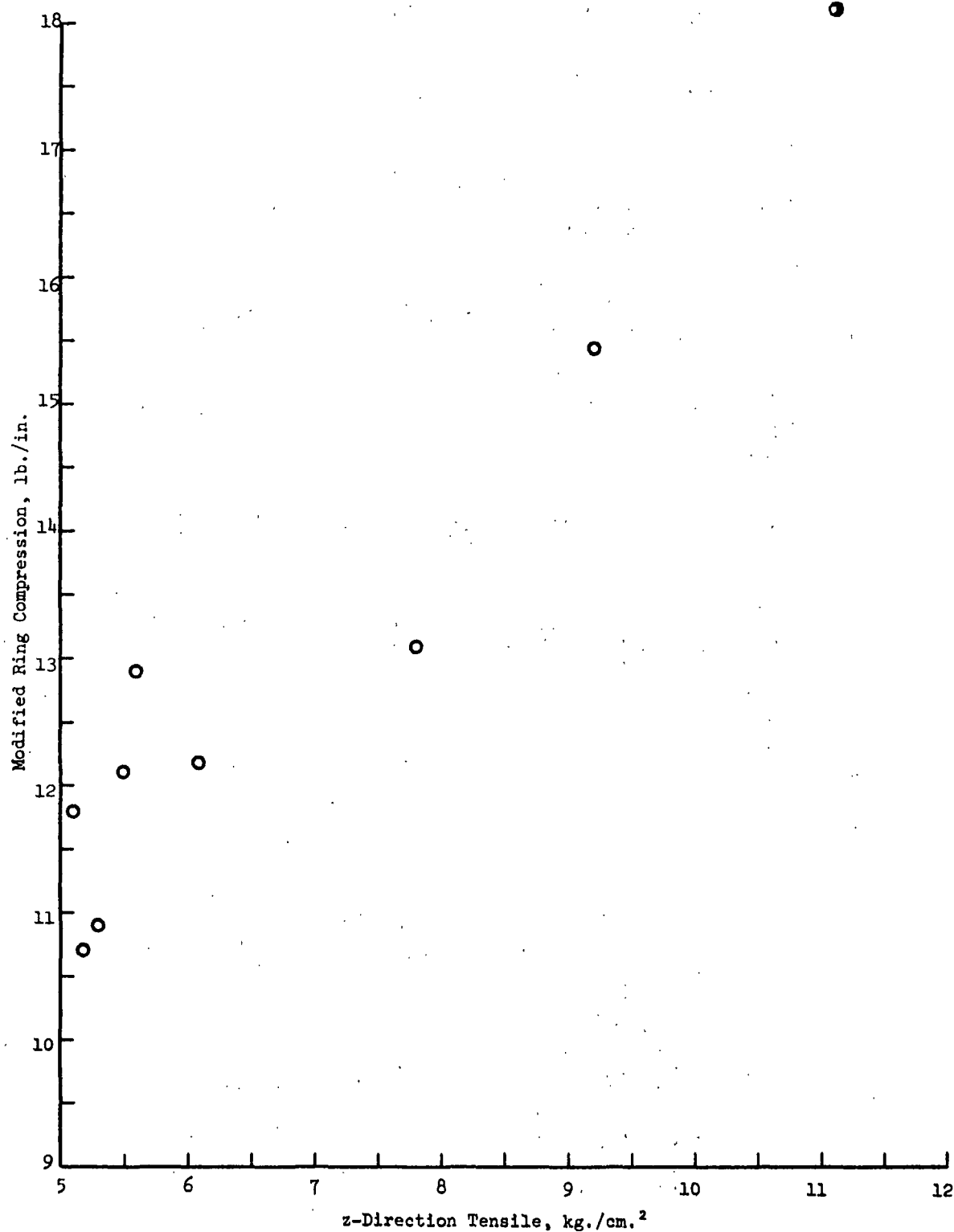


Figure 2. Relationship Between z-Direction Tensile and Modified Ring Compression Strength for Sheets Prepared with Varying Amounts of Wetting Agent (350-cc. Freeness)

reducing the bonding strength effected large reductions in modified ring strength. An approximately linear relationship is obtained. Similar results were obtained at the other freeness levels. Thus, these results are in direct contrast to the previous results where bonding strength was increased above the "normal" level.

#### UNBONDED FIBERS

As one means of varying the degree and uniformity of bonding, varying percentages (up to 30%) of rayon fibers were incorporated in the furnish. The rayon fibers do not bond to the cellulose fibers, hence their presence should produce localized regions of lower bonding strength — the extent of such regions would depend on the level of addition. The results obtained are summarized in Table V and are illustrated in Fig. 3. It may be noted that z-direction tensile decreased in an approximately linear manner with increasing amounts of rayon fiber. At the 30% addition level the reduction in z-direction tensile strength was 54.4%. At the 20 and 30% addition levels substantial decreases in modified ring strength were also obtained — 34.7% reduction at the 30% addition level. For low levels of rayon fiber addition the ring strength was somewhat higher than the control although this may be due to test variability. In any case, the results may indicate that ring strength is not necessarily sensitive to local bonding deficiencies.

#### STOCK HEATING EFFECTS

As another means of varying the bonding the stock was heated to the boiling point after which handsheets were prepared in the usual manner. The heating would be expected to "deswell" the fibers and result in lower bonding strength levels. Two trials were made as shown in Table VI. In the first trial somewhat lower z-direction tensile strengths were obtained for the stocks



heated for 5 and 15 minutes but the ring compression results exhibited little or no change. In the second trial somewhat greater reductions in z-direction tensile strength were obtained for the shorter heating times. Significant reductions in modified ring strength were also obtained.

TABLE V  
EFFECT OF VARYING AMOUNTS OF UNBONDED FIBER  
(350 cc. C.S. Freeness)

Synthetic Fiber, %	Basis Weight, lb./M ft. <sup>2</sup>	Caliper, pt.	z-Direction Tensile, kg./cm. <sup>2</sup>	Diff., % <sup>a</sup>	Modified Ring Compression, lb./in.		Diff., % <sup>a</sup>
					As Tested	Adjusted <sup>b</sup>	
0 (Control)	28.0	7.2	11.4	--	18.0	16.7	--
1	27.8	7.1	11.3	- 0.1	20.2	18.9	+13.2
5	27.3	7.6	10.7	- 6.1	18.2	17.3	+ 3.4
10	27.4	7.9	9.26	-18.8	16.9	16.0	- 4.2
20	26.0	8.5	6.66	-41.6	13.2	13.2	-21.0
30	25.2	9.0	5.20	-54.4	10.6	10.9	-34.7

<sup>a</sup>Based on Control as reference.

<sup>b</sup>Adjusted to 26 lb./M ft.<sup>2</sup>

#### LOCALIZED BONDING FLAWS

In an attempt to study the effect of localized bonding deficiencies small rectangular pieces of dry tissue were placed between two 13-lb. sheets and the composite sheet was then wet laminated, pressed and dried in the usual manner. Similar experiments were carried out using an unbalanced combination of 9 and 17-lb. handsheets. It would be anticipated that the bonding between the tissue insert and the fibers on each side of it would be much less than would

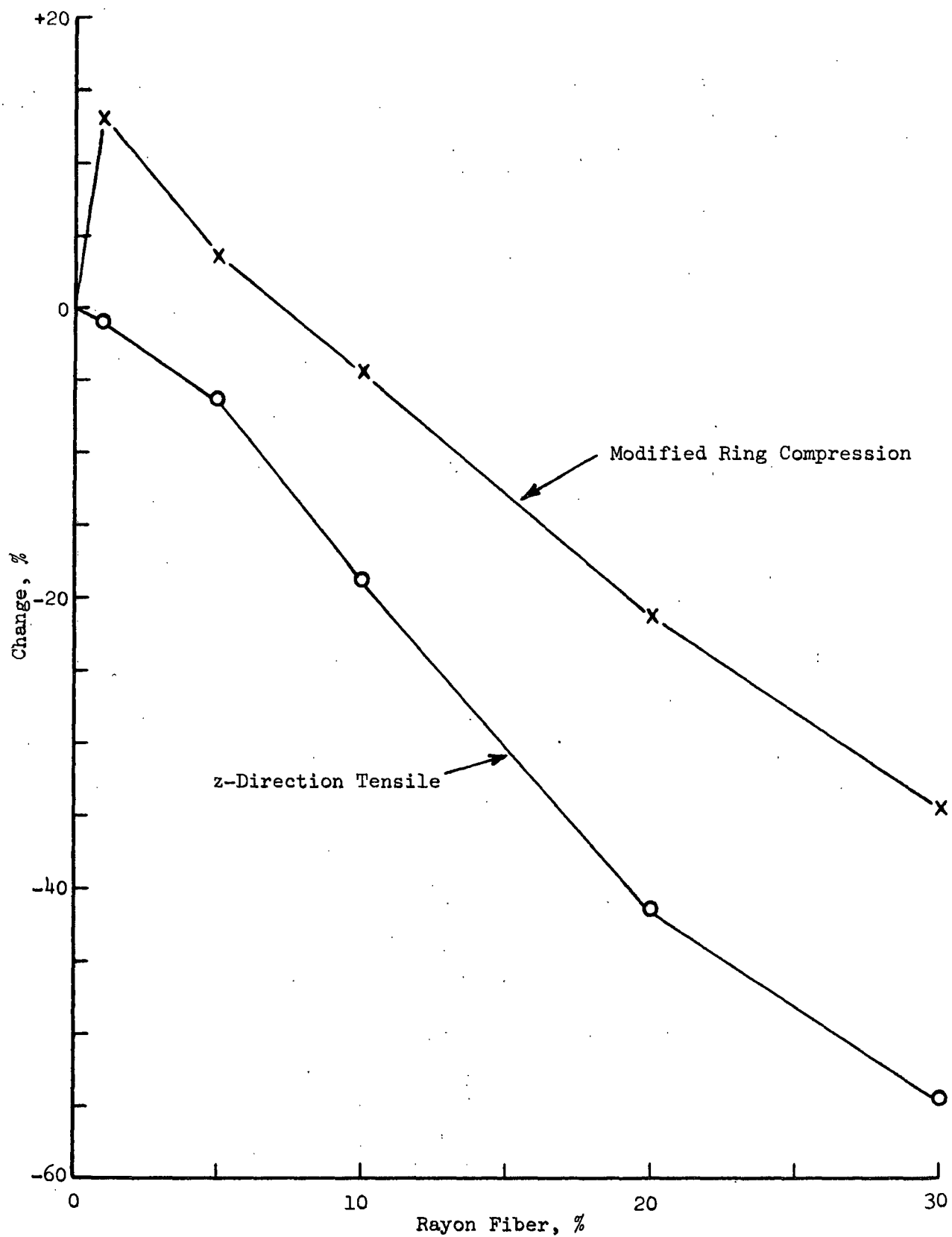


Figure 3. Effect of Synthetic Fiber Content on z-Direction Tensile and Modified Ring Compression Strength

TABLE VI  
EFFECT OF VARIATIONS IN BONDING ON EDGEWISE COMPRESSION

Experiment	Conditions	Freeness, cc.	Basis Weight lb./M ft. <sup>2</sup>	Caliper, pt.	z-Direction Tensile, kg./cm. <sup>2</sup>	Diff., %	Mod. Ring Compression, lb./in.		Diff., %
							As Tested	Adjusted <sup>b-</sup>	
1-A	Control	350	27.9	7.2	11.0	--	19.1	17.8	--
1-B	Stock heated to 212°F.	370	28.8	7.4	11.2	+ 1.8	20.1	18.1	+ 1.7
1-C	Stock heated 5 min. at 212°F.	390	27.8	7.1	10.3	- 6.4	17.7	16.6	- 6.7
1-D	Stock heated 15 min. at 212°F.	465	28.1	7.6	9.6	-12.5	19.6	18.1	+ 1.7
1-AR	Control	350	28.2	7.1	12.4	--	19.9	18.3	--
1B-R	Stock heated to 212°F.	445	27.9	7.8	9.5	-23.7	16.4	15.3	-16.4
1C-R	Stock heated 5 min. at 212°F.	500	28.5	7.8	10.7	-13.7	17.2	15.7	-14.2
1D-R	Stock heated 15 min. at 212°F.	560	27.8	7.5	11.4	- 8.1	18.1	16.9	- 7.7
1-AR-2	Control wet pressed at 100 p.s.i.	350	28.7	7.0	13.5	+ 8.9	19.4	17.6	- 3.8

<sup>a</sup>Based on Control as reference.

<sup>b</sup>Adjusted to a basis weight of 26 lb./M ft.<sup>2</sup>

normally be obtained. Therefore, if failure in edgewise compression strength were limited by fiber bond failures in localized regions it was conjectured that failure would originate in the tissue regions and result in lower compression strength.

The results obtained are summarized in Table VII. The above expectations were not borne out by the results. In general, the compression results were higher than the control for all tissue insert sizes even though substantial reductions in z-direction tensile strength were obtained in some cases. However, failure did not occur in the region of the tissue inserts. The failure lines generally ran along the long edge of the tissue and then proceeded in more random way along the remainder of the specimen. Thus, stress concentration effects along the edges of the inserts apparently were instrumental in directing the failure line. Consequently, failure did not occur in the tissue insert region where the stress would be expected to be somewhat lower due to the higher caliper in this region.

#### SYNTHESIS OF RESULTS

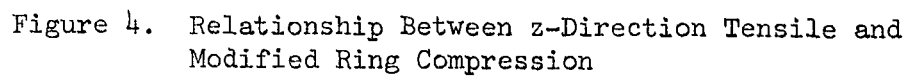
An overall view of the results from the several phases of the study is provided by plotting z-direction tensile vs. modified ring compression strength. Figure 4 shows a portion of the results for sheets made at 350 cc. It may be noted that when the z-direction tensile strength is below about 10 to 12 kg./cm.<sup>2</sup> edgewise compression strength is fairly sensitive to changes in z-direction tensile strength. When the fiber bonding as measured by z-direction tensile strength is increased beyond the 10-12 kg./cm.<sup>2</sup> range edgewise compression strength remains nearly constant or increases very slightly. (Note: The lines shown in the graph were fitted by "eye" to draw attention to the main trends.)

TABLE VII  
EFFECT OF LOCAL BONDING FLAWS ON EDGEWISE COMPRESSION STRENGTH

Experiment	Conditions	Freeness, cc.	Basis Weight, 2 lb./M ft.	Caliper, pt.	z-Direction Tensile kg./cm. <sup>2</sup>	Diff., %	Mod. Ring Compression, lb./in.		Diff., %
							As Tested	Adjusted <sup>b</sup>	
4-A	Control, 2 13-lb. sheets; no tissue	350	28.1	7.4	10.4	--	16.7	15.5	--
4-B	1/16 x 1 in. tissue insert	--	28.0	7.2	10.4	0.0	16.8	15.6	+ 0.6
4-C	1/8 x 1 in. tissue insert	--	28.3	7.2	9.8	- 5.8	17.5	16.1	+ 3.7
4-D	1/4 x 1 in. tissue insert	--	27.2	7.3	7.0	-32.7	17.7	16.9	+ 9.0
4-E	Control, 1 17, 1 9-lb. sheets; no tissue	350	27.2	7.1	11.7	--	17.0	16.2	--
4-F	1/16 x 1 in. tissue insert	--	28.6	7.3	8.7	-26.4	18.0	16.4	+ 1.2
4-G	1/8 x 1 in. tissue insert	--	27.9	7.2	9.1	-22.2	17.7	16.5	+ 1.8
4-H	1/4 x 1 in. tissue insert	--	28.0	7.2	8.3	-29.1	19.0	17.6	+ 9.0

<sup>a</sup>Based on Control as reference.

<sup>b</sup>Adjusted to 26-lb. basis weight.



These results suggest that edgewise compression strength is dependent on at least two factors. They are: (1) the compression-buckling strength of fiber segments in the sheet, and (2) the number and strength of the bonds. Thus, as the degree of bonding is increased from low levels approximately proportionate increases in edgewise compression strength are obtained at first because more and stronger bonds are developed between fibers. The better bonding allows the fiber segments to support more load before they buckle and fail. However, beyond a certain level of fiber bonding (roughly 10-12 kg./cm.<sup>2</sup> z-direction tensile in this study) compression strength is little affected by further increases in fiber bonding. Relatively large increases in z-direction tensile strength effect either no or small increases in edgewise compression strength in this region. This suggests that fiber resistance to compression-buckling stresses becomes the limiting factor above a certain degree of bonding.

The above seems consistent with the observation that edgewise compression strength is only weakly influenced by many process variables. Much the same behavior has been noted in the case of properties dependent on the moduli of the sheet — e.g., tensile and bending stiffness. Van den Akker's (2) work some years ago indicated that the tensile moduli of the sheet would be expected to depend on both the elastic moduli of the fibers as well as the distribution and strength of the bonds. Setterholm, et al. (3) have presented evidence to show that the compression and tensile moduli are approximately equivalent.

It is interesting to note that Giertz (4) has reported results showing that tensile strength behaves in a somewhat similar manner with bonding strength as was found herein for compression strength. He prepared sheets from a series of sulfite pulps representing a wide range of beating and pressing conditions.

The resulting tensile strength-density diagrams exhibited two principal regions — a region where strength increased with density followed by a region where strength was more or less unaffected by density. Taking density as a measure of bonding, Van den Akker (5) has commented that these results may be explained as follows: "For tensile strength up to a certain level (depending, significantly, on the degree of chemical degradation of the pulp) f-f [fiber-to-fiber] bonding controls the initiation of failure and for degrees of bonding beyond that level, the initiation is controlled by the strength of the fibers, per se." The similarity between Giertz's results and the results obtained herein is striking.

In paper the original tubelike fibers are flattened. Springwood fibers assume a ribbonlike appearance while summerwood fibers appear much like flattened ovals. Van den Akker (5) has pointed out that a typical fiber may be bonded "to 30 or more fibers in 1 mm. of length." Thus, the average segmental width between bond centers is relatively short. Hence, the action of forces over relatively short lengths of fibers is of importance. This may be of particular importance in compression where buckling in stability could be involved.

Page and Tydeman (6) have observed that microcompression deformation occurs in a fiber when a crossing fiber shrinks. This observation can be invoked to explain the substantial shrinkage which occurs in drying. It also can affect the sheet moduli. For example, Van den Akker (5) has commented that the degree of microcompression of the fibers would be expected to be less when a sheet is dried under tension and this would increase the modulus of the sheet as well as the fiber. Jentzen (7) has shown that the tension modulus and strength of fibers can be increased by drying them under tension. This effect was attributed to changes within the fiber which permit the microfibrils



to share loads more equally on subsequent straining of the dried fiber. These observations direct attention to the important effects of drying tension on the resulting tension properties of the fiber and sheet. They also apply in general to compression behavior, although some differences in the magnitudes of effects may be expected when tension and compression behaviors are compared.

As one example, the tension properties of machine-made boards normally exhibit a much greater directional effect than edgewise compression strength. For fourdrinier-made boards, the tensile grain ratio is typically near 2.0 while the compression grain ratio is 1.3 to 1.4. For cylinder-made boards, tensile and compression grain ratios may be near 4.0 and 2.0, respectively. Tensile strength and tensile stiffness exhibit similar grain ratios and Setterholm's (3) work indicates that compression stiffness grain ratios would be about the same as in tension. Thus, the compression response at failure is affected somewhat differently by directional effects than are the tension properties or compression moduli.

It is well known that there is a fairly good relationship between tensile stiffness and edgewise compression strength. More than likely, consideration of other factors such as bonding strength would improve such relationships. Some confirmatory evidence for this has recently been developed in other areas.

Further work to explore the validity of the trends developed in this work appears warranted. Certainly it would be of interest to develop more information relative to the effect of fiber strength at various levels of bonding. The use of sheets formed from synthetic fibers varying in strength may be one approach to this subject.

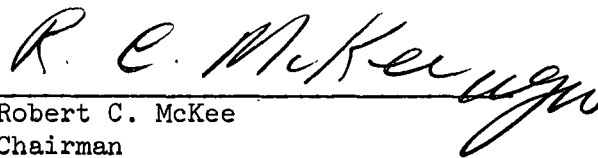
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